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Geotechnical and Geological Characterization and Ambient Vibration Study of Shallow Geological Units in Barreiro and Setúbal Areas (Portugal)

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Abstract

Barreiro and Setúbal are two regions located within the Metropolitan Area of Lisboa (Portugal) that may suffer from high losses due to earthquake occurrence. The objectives of this study were to evaluate the relationships between the geological and geotechnical properties of the shallower units with horizontal-to-vertical spectral ratio (H/V), looking for potential side effects. The geotechnical characterization was based on the analysis of 4064 Standard Penetration Tests (SPT) compiled in 676 boreholes of 96 geotechnical reports. Fundamental (F_0) and predominant (F_1) frequencies and corresponding amplitude peaks were obtained with 249 ambient vibration records carried out with a Güralp CMG 6TD broadband station. Data regarding SPT, thickness of surface units (Holocene), depths of the substrate (Pliocene and Miocene), F_0 and F_1 and respective amplitude peaks were analysed. The thickness of Barreiro Holocene (anthropogenic and alluvial deposits) was related to F_0, F_1 and SPT values. The spatial distribution of F_0 and F_1 allowed the definition of two surfaces.
The first one corresponds to the boundary between the Holocene and the Pliocene (4-32 m deep) and the second one to the boundary between the Pliocene and the Miocene (250 m deep). Three areas prone to seismic amplification with frequencies between 2.5 to 8 Hz were identified. In Setúbal, it was not possible to establish a relationship between the thickness of the surface units and F_0 and F_1.

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Keywords: side effects; H/V spectral ratio; SPT; geotechnical characterization.

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A possible cause may be that the impedance contrast between the Holocene and Pliocene is not strong enough to cause frequency peaks in the H/V curves. Setúbal's downtown presents F_0 between 1 to 3 Hz with amplitude peaks between 3 and 8. These results are aimed to use in land planning policies and emergency plans.

1. Introduction

Although the Metropolitan Area of Lisbon shows a moderate seismicity due to its geotectonic location, it has been subjected to catastrophic earthquakes responsible for high social and economic losses in the past. Earthquakes of 1755 ($M \geq 8$), 1858 ($M \approx 7$) and 1909 ($M \approx 6$) are the examples of destructive events that hit this region. Barreiro and Setúbal are two regions located in this area of Portugal, which may be subjected to the effects of future earthquakes. During the 1858 earthquake the city of Setúbal suffered an intensity of IX (you mentioned 7 previously) (MMI – Mercali Modified Intensity). The characteristics of seismic ground motion can be locally modified due to the existence of shallow soft surface layers where damages may be increased by seismic wave amplification, usually denominated as side (correct further in the article) effect (Bakavoli et al. 2012). This phenomenon which occurred in many earthquakes, such as the ones at Michoacán and Kobe (Mirzaoglu et al. 2003). Side effects have been widely studied (García-Fernández and Jiménez 2012, Navarro and García-Jerez 2012) using Nakamura's technique (Nakamura 2008). This technique is based on the interpretation of the horizontal-to-vertical spectral ratio (H/V) computed from ambient vibrations records. The objectives of this study were the estimation of side effects and the evaluation of the relations between the geological and geotechnical properties of the shallower units with horizontal-to-vertical spectral ratio (H/V) for Barreiro and Setúbal (Figure 1).

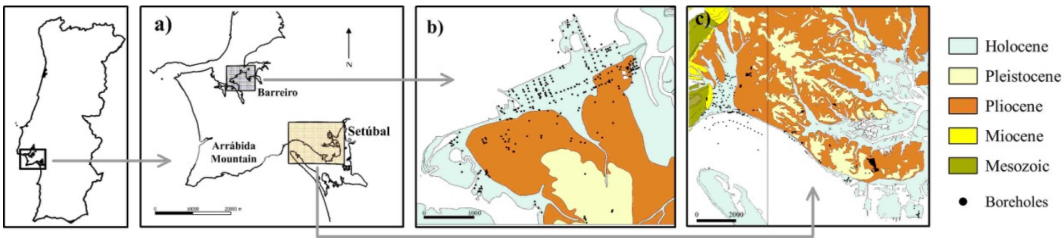

Fig. 1. (a) The study area; (b) geology of Barreiro; (c) geology of Setúbal. Black dots indicate the location of boreholes.

2. Methodology

Geological and geotechnical data were compiled from the reports and an ambient vibrations survey was carried out. QGIS (http://qgis.osgeo.org), RockWorks15 (https://www.rockware.com/) and Geopsy software (http://www.geopsy.org/index.html) (put the links into the references or footnote) were used for storage, processing and data modelling using the inverse-distance algorithm. Maps of shallower unit's thickness, N_{SPT60} surface, distribution of peak frequencies, respective amplitudes were produced, and areas prone to side effects were identified.

2.1. Geological and geotechnical characterization

The geological setting of the study areas is characterized by Cenozoic formations, mainly sedimentary series (Pais et al. 2006, Manuppella et al. 1994) (Figures 1b and 1c). Pliocene and Pleistocene have a predominantly sandy sequence, while Holocene deposits are characterized by a sequence of sandy and clayey lenticular beds with lateral and vertical facies variations. Heterogeneous anthropogenic deposits are also present. The western limit of Setúbal is confined by the Mesozoic formations of Arrábida mountain ridge. 96 geotechnical reports were analysed and information on 676 boreholes (Figures 1b and 1c), logs and 4064 Standard Penetration Tests (SPT) was compiled. In this study, three geological units were considered, namely: landfills, alluvial and substrate (Pliocene or Miocene).

2.2. Ambient vibrations records

Ambient vibrations records were carried out in 249 sides. Records were done using a Güralp CMG 6TD broadband station, according to guidelines defined in SESAME (2004). Most recordings were performed for 30 minutes in urban areas, between 1 and 4 AM. H/V spectral ratios were calculated and fundamental (F_0) and predominant (F_1) peak frequencies, with the respective amplitudes (A_0 and A_1), were identified. The fundamental peaks were converted into sediment thicknesses (H) using the following equations from Parolai et al. (2002) and Ibs-von Seht and Wohlenberg (1999), respectively $H=108F_0^{-1.551}$ and $H=96F_0^{-1.388}$. The obtained sediment thicknesses were compared with the thickness of shallower units and N_{SPT60} surface obtained from geotechnical reports.

3. Results and discussions

Greater thickness areas of shallower units were observed in Barreiro and Setúbal's Holocene (Fig. 2a, 2b). Thickness showed values greater than 30 m in old piped water lines and landfills reclaimed to river and sea areas. In those areas, N_{SPT60} surface reached elevations of -18.8 m in Barreiro and more than -30 m in Setúbal (Fig. 2c, 2d).

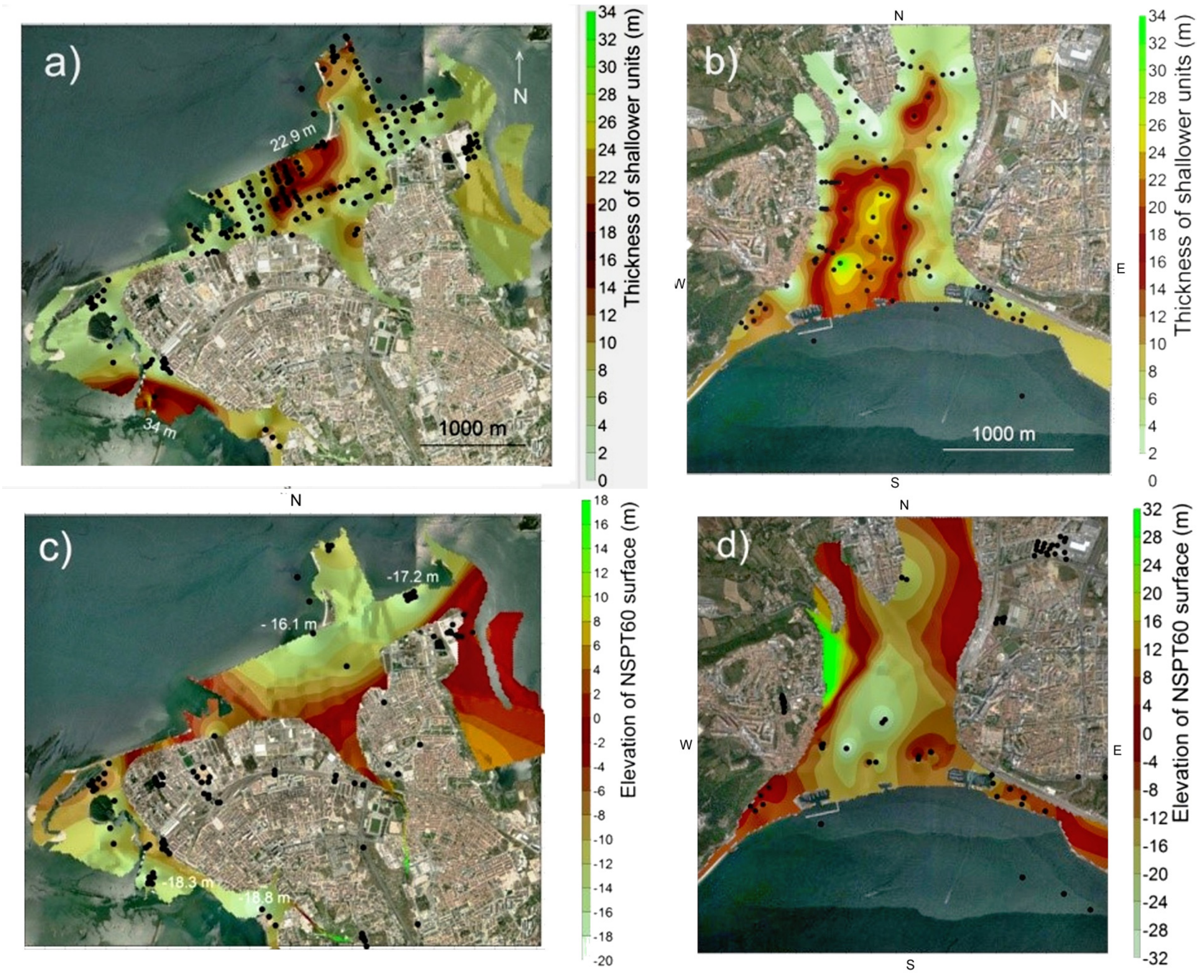

Fig. 2. Thickness of shallower units based on boreholes data (a) Barreiro, (b) Downtown Setúbal, and elevation of $NSPT_{60}$ surface (c) Barreiro, (d) Downtown Setúbal. Black dots indicate the location of boreholes; in (c) and (d) only boreholes with SPT.

N_{SPT} data showed mean values of 10 in both areas for landfills, of 8 (Barreiro) and 28 (Setúbal) for alluvial deposits, and of 48 (Barreiro) and 60 (Setúbal) for PlioPleistocene formations.

Barreiro's Holocene and PlioPleistocene exhibited a large area with F_0 between 0.6 and 0.7 Hz. Barreiro's Holocene showed F_0 between 3 and 8 Hz and PlioPleistocene formations displayed H/V curves without frequency peaks (typical of rock outcrop) (Figure 3a). Barreiro´s Holocene also exhibited F_1 between 2 and 8 Hz. The eastern area of Setúbal presented F_0 between 0.7-0.8 Hz, increasing to the west up to the Arrábida mountain ridge, where the highest values were obtained (12 Hz). In this zone, curves without frequency peaks were also observed (Figure 3b).

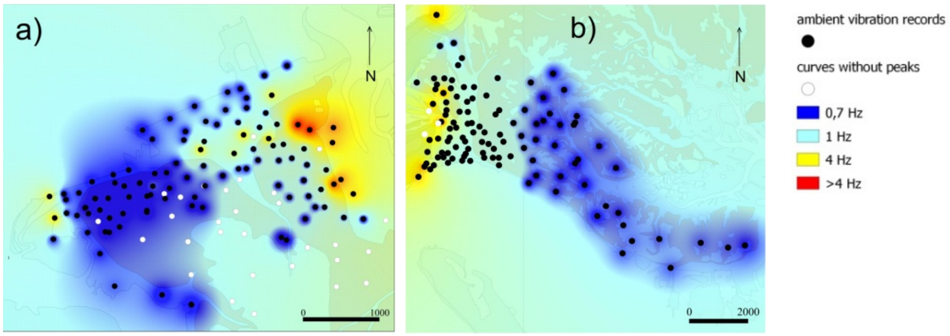

Fig. 3. Distribution of peak frequencies in (a) Barreiro and (b) Setúbal. Black dots indicate the location of ambient vibrations records. White dots indicate curves without peaks.

Figure 4 shows zones prone to side effects. The amplitudes of the F_0 peaks along Barreiro's Holocene vary for a range of frequencies between 2.5-8 Hz (Figure 4a). Setúbal's downtown presented the higher A_0 of this study area, ranging between 3.4 and 7.7, for F_0 between 1-3 Hz (Fig. 4b).

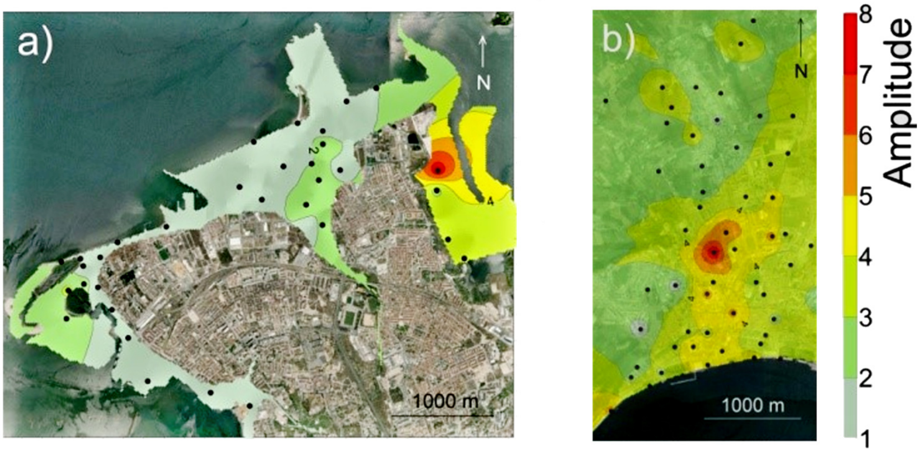

Fig. 4. Amplitude (A_0) distribution in (a) Barreiro and (b) Setúbal downtown. Black dots indicate the location of ambient vibrations records.

Due to its best adaptation to geotechnical data, the equation defined by Parolai et al. (2002) was applied to Barreiro's F_0 frequencies (0.5-0.6 Hz). It was possible to associate the obtained depth, 250 m, to the Pliocene-Miocene boundary (Figures 5a and 5b). This value is compatible with the values observed in boreholes (260 m; CPP 1963) and obtained with seismic prospecting data (250 m; Lomholt et al. 1995). When applying an equal methodology to the Holocene areas using F_0 and F_1 (2.2-8.1 Hz) it was found that both were probably associated with the boundary between shallow units and Pliocene formations (Fig. 5b and 5c).

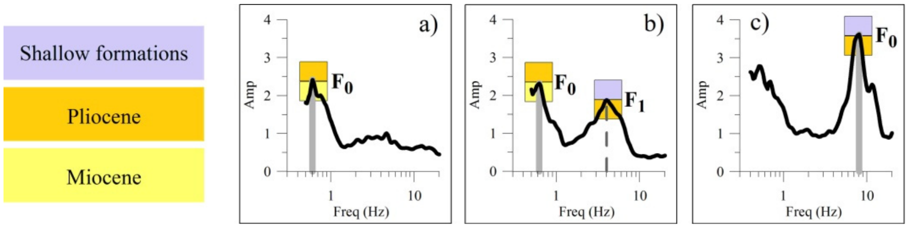

Fig. 5. Relationship between F_0 and F_1 with Barreiro´s geological boundaries in 3 different sampling areas (a, b and c).

The thickness of shallow formations in Barreiro´s Holocene was calculated applying the equation of Parolai et al. (2002) to F_0 and F_1 (34 H/V peaks between 2.2 and 8.1 Hz) (Figure 6a). Figure 6b shows the difference between the thicknesses of shallow formations calculated with H/V peaks (Figure 6a) and with boreholes (Figure 2a). The areas with lower differences (0 ± 4 m) correspond mainly to the areas of greater thickness of shallow units (Figure 2a) or to the areas with data regarding both ambient vibrations and boreholes (Figure 6b).

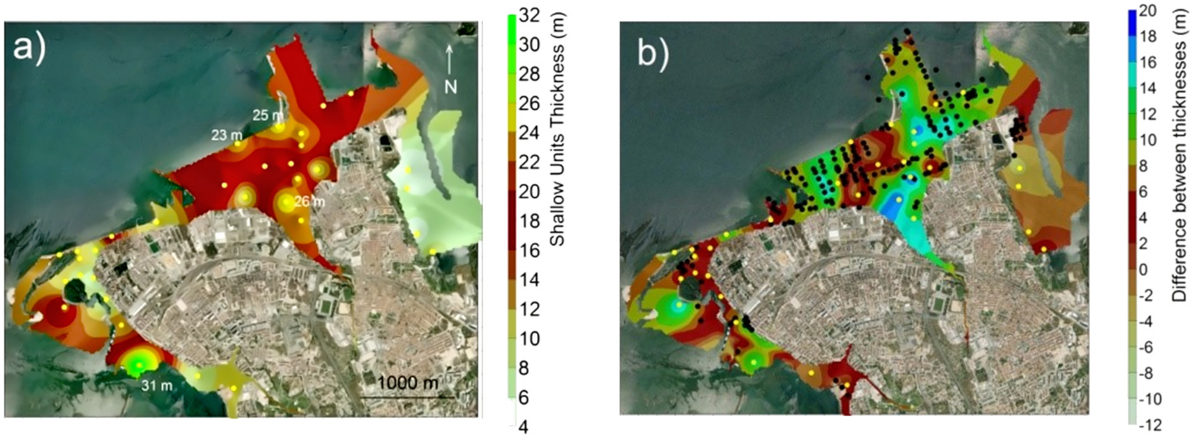

Fig. 6. (a) Thickness of shallow formations calculated with H/V peaks; (b) difference between the thicknesses of shallow formations calculated with H/V peaks and with borehole data in Barreiro's Holocene. Yellow dots indicate the location of ambient vibrations records; black dots indicate the location of boreholes.

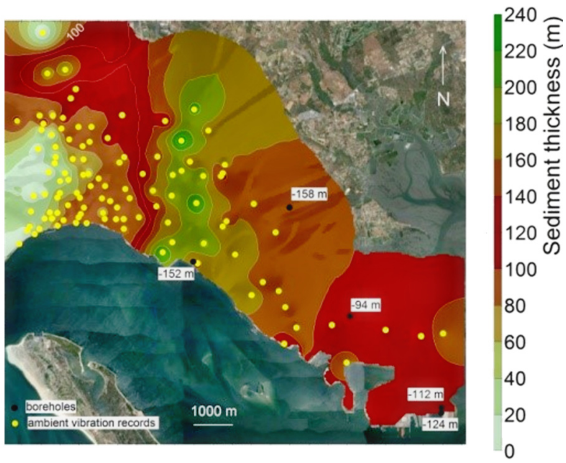

Fig. 7. Relation between the Pliocene-Miocene boundary obtained with borehole data and by Ibs-von Seht and Wohlenberg (1999) equation in Setúbal. Yellow dots indicate the location of ambient vibrations records; black dots indicate the location of boreholes.

The comparison among the thicknesses of shallow formations based on borehole data (Figure 2a), N_{SPT60} surface (Figure 2c) and thicknesses calculated with H/V (Figure 6a) showed some similarities in the geographical distribution of the values. Higher values observed in borehole data (34 and 22.9 m) correspond to the higher values calculated with H/V (31 and 25 m) and to the lower values of N_{SPT60} surface (-18.3 and -16.1 m).

The application of Parolai et al. (2002) and Ibs-von Seht and Wohlenberg (1999) equations to Setúbal revealed that F_0 and F_1 were not associated with the boundary between shallow units and Pliocene. This situation is probably because the seismic impedance contrast around that boundary is too weak to produce frequency peaks, as already suggested by Coelho (1980) for seismic refraction results. By applying the equation defined by Ibs-von Seht and Wohlenberg (1999) to Setúbal's F_0 frequencies (0.6-10 Hz), the sediment thickness (Holocene and PlioPleistocene) for this area was obtained (Figure 7). It was possible to associate that thickness with the Pliocene-Miocene limit obtained in boreholes (Sondagens e Fundações A. Cavaco 1971a, 1971b).

4. Conclusions

Barreiro's Holocene and Setúbal downtown are densely urbanized and might suffer from great damages in the future events. Frequency peaks (F_0, F_1) can be related with the limits between geotechnical and geological units upon the impedance contrasts. Besides, the distribution of the amplitude of these frequency peaks is an indicator of areas prone to side effects.

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